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CLOSED LOOP CONTROLLED HIGH SPEED INDUCTION GENERATORS USING ADAPTIVE CONTROL TECHNIQUE (PREPRINT)

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14. ABSTRACT
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High speed generators offer a very high power density solution for electric power requirements in airborne applications. Induction generators are suitable for the high speed environment because of the ability to provide controlled voltage and power output with a reliable rotor construction. An important issue of power control for the high speed induction generator is maintenance of the steady state output voltage within the specified limits over the entire range of speed and load variations. This paper discusses the development of a closed loop control system for a 200 kW induction generator under different load conditions.

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Closed Loop Controlled High Speed Induction Generators Using Adaptive Control Technique

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ABSTRACT

High speed generators offer very high power density solution for electric power requirements in airborne applications. Induction generators are suitable for the high speed environment because of the ability to provide controlled voltage and power output with a reliable rotor construction. An important issue of power control for the high speed induction generator is maintenance of the steady state output voltage within the specified limits over the entire range of speed and load variations. This paper discusses the development of a closed loop control system for a 200 kW induction generator under different load conditions.

Field Oriented Control (FOC) schemes are implemented to both operate the generator in the maximum torque conditions available and to decouple the maximum torque from the field under transient and steady state operation. FOC uses Classical Proportional and Integral (PI) controllers for regulation because of their simple implementation. However, PI controllers do not perform well when controlling high order non-linear dynamic plants - such as the high speed induction generators - due to the overshoot response and the output saturation when generator is loaded.

To resolve this issue, the proportional gains need adjustments with respect to the load variation as well as the overshoot response in real-time.

A gain scheduling control algorithm has been developed to select the appropriate controller gains with respect to the generator load. Further, a relationship between the generator loads and the controller gains have been established. This relationship was modeled using adaptive control technique to vary the gains automatically under any load condition.

The adaptive control technique has been successfully generalized for real time DSP implementation to regulate the DC voltage for high speed induction generators rated from 5 kW to 200 kW. .

INTRODUCTION

In order to maintain a constant voltage at the generator terminals, its excitation current needs to be adjusted during load variation from no load to full load. This is accomplished with the use of a PI controller. When a sudden step load is applied, the PI controller can become unstable. The transient voltage response was not well controlled with a conventional PI control scheme. Two issues have been identified: (1) overshoot response caused by a large error between the DC voltage command to the sensed DC voltage. (2) The voltage response

between step loads is very slow due to the fixed proportional and integral gains. The source of this issue is that PI controller gains cannot be set to satisfy both the overshoot and load variation simultaneously.

To overcome this issue, the proportional gains need adjustments with respect to the load variation as well as the overshoot response in real-time. A gain scheduling control algorithm has been developed. This algorithm represents a set of linear controllers, each of them designed for a specific load condition. Thus, when the generator is under a certain load condition, the algorithm control signal determines which linear controller to activate. The gain scheduling algorithm was implemented successfully to regulate the DC voltage at load conditions where the gains were predetermined.

Later a relationship between the proportional, integral gains and the load conditions has been established. The relationship allowed the development of an adaptive control technique to vary the gains automatically at any load condition. The adaptive control technique has been tested from 0 to 5 kW.

GENERATOR CLOSED LOOP CONTROL

For high performance control, FOC algorithm is implemented. The algorithm transforms the three phase sinusoidal currents from the stationary reference frame to DC quantities in rotating reference frame. The rotating reference frame is composed of the direct current component and the quadrature current component which are to be orthogonal to each other.

To maintain a constant DC output voltage, the excitation current need to be adjusted accordingly to the generator load condition. The closed loop algorithm includes a special case of the indirect FOC scheme [1]. It is based on selecting the D-Q axes so that the direct current and the quadrature current are equal. Equation 1 shows the developed torque.

$$T = \frac{1}{2} K_T I_{DQ}^{\ 2} \quad \textbf{(1)}$$

Equation (1) summarizes the mechanism of the generator closed loop algorithm. The closed loop algorithm block diagram is shown on Figure 1.

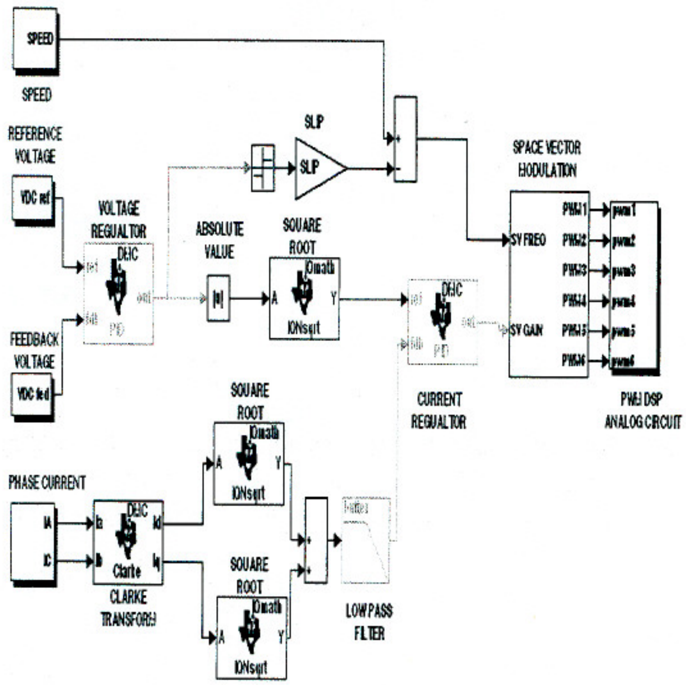

Figure 1: Generator closed loop algorithm

The commanded voltage, measured generator bus voltage, measured shaft speed, and measured three phase ac generator currents are the inputs to the algorithm. The total $I_{DQ}^{\ 2}$ current is calculated from the current feedback loop and also from the difference between the output voltage and the voltage command.

Both currents are compared and based on the error; the (PI) current regulator generates the necessary switching commands for the six switches in the three-phase full bridge inverter using space vector modulation technique.

Gain scheduling method

Finding the gains for each load condition was the key to appropriately regulate the voltage. The closed loop algorithm was developed with the capability to change K_p and K_i as the generator load varies in real-time. Transient tests were conducted to find the gains at 44000 RPM at no load then at 32.8 kW and 48.6 kW.

Ziegler-Nichols Tuning Method

The search for K_p and K_i in the unstable regions has been conducted through transient tests. The gains were obtained using Ziegler-Nichols tuning method [2], since the generator is not been modeled mathematically. The procedure of this method is conducted by setting K_p to a low value and K_i to zero. Then a voltage step is applied at no-load and under 32.8 kW and 48.6 kW to investigate the DC voltage transient.

When the PI output oscillations decayed, K_p had to be increased. Then, when the oscillations increased in amplitude (unstable system), K_p had to be reduced. At the point of stability, K_i is set to a small value to eliminate the steady state error. This method is iterated until the stable range over which K_p and K_i varied is obtained. A constant value of K_i is found to be adequate but K_p increased by 36 % under the step load of 32.8 kW to 48.6 kW.

Table 1 shows the values for K_p and K_i under 0, 32.8kW, and 48.6 kW load conditions.

POWER, kW	REG VOLTAGE, Volt DC	K_p	K_i
0	270	0	9000
32.8	270	1100	9000
48.6	270	1500	9000

Table 1 : K_p and K_i under two load conditions.

After gathering K_p and K_i with respect to their load conditions, these values were programmed into a closed loop scheduling algorithm. Figure 2 shows the scheduling algorithm block diagram.

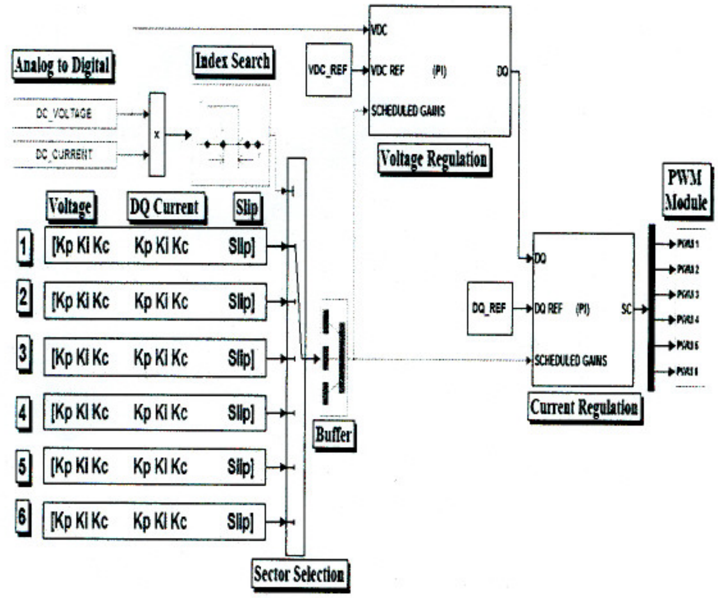

Figure 2: Generator closed loop scheduling algorithm

The product between the DC voltage and the DC current signals is established to obtain the power. The power value is processed in a look up table to search for the pre-selected gains.

These gains are reserved in an array and stored until triggered by the power value. Based on the load, the PI regulator receives the corresponding gains for that condition.

Figure 3 illustrates the responses of the DC voltage, DC current and space vector command respectively under the tested load conditions.

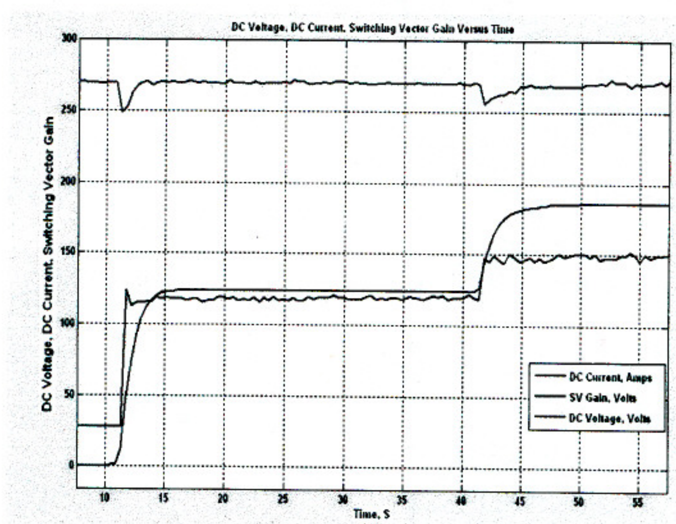

Figure 3: DC voltage, DC current and space vector command versus time

The gain scheduling method has been successfully implemented to regulate DC voltage of the 200 kW generator. The technique was demonstrated under various loads from no load to 48.6 kW.

ADAPTIVE CONTROL UNDER ANY LOAD CONDITION

The gain scheduling method discussed previously is further developed to maintain a constant DC voltage of the generator to any load condition.

The idea was to implement an algorithm that automatically regulates K_p according to a load condition. To develop this kind of algorithm, a relationship between K_p, K_i and power needs to be established. However, in the case of the 200 kW generator, a constant value of K_i was found to be adequate. Only K_p and power relationship needed to be established.

Based on the gain scheduling transient tests data, proportional gains were fitted through polynomial curves to represent this relationship. Figure 4 illustrates K_p versus power.

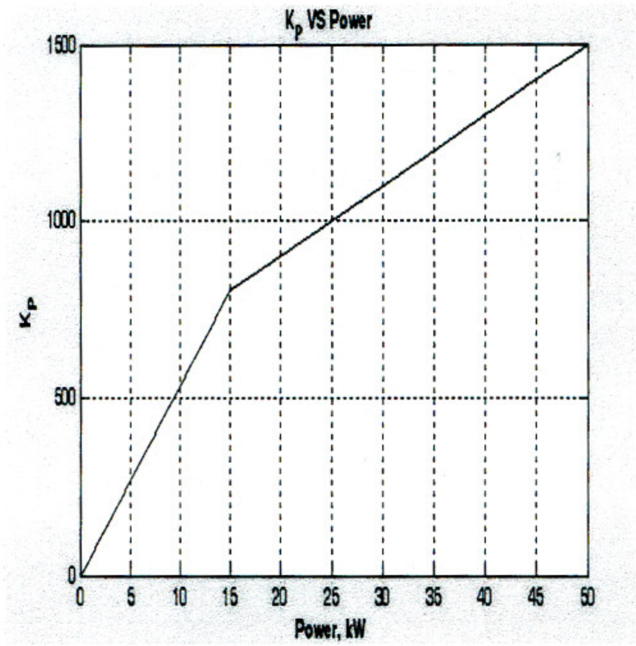

Figure 4: K_p versus power

Analysis of curve fitting has been conducted for first and second order polynomial to find the best fit. Figure 5 illustrates the curve fit for the first and second order polynomial.

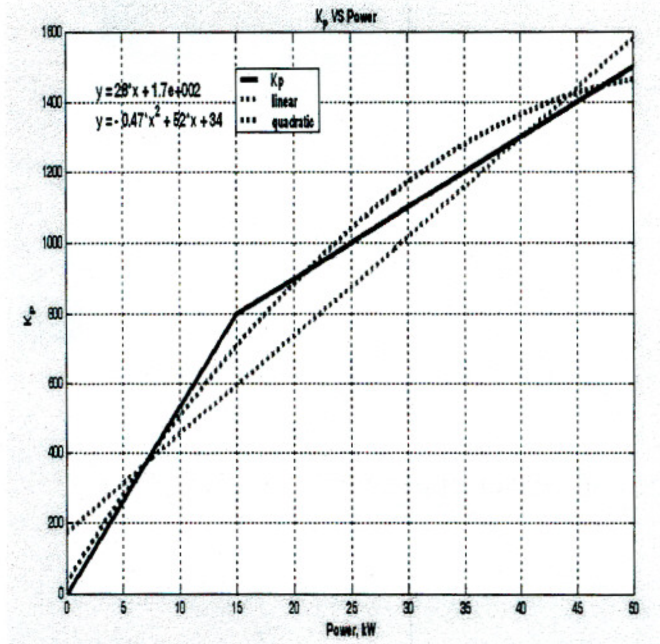

Figure 5: First and second order polynomial

SECOND ORDER POLYNOMIAL

The second order polynomial was implemented and tested. Figure 6 below illustrates the curve fitting and offsets.

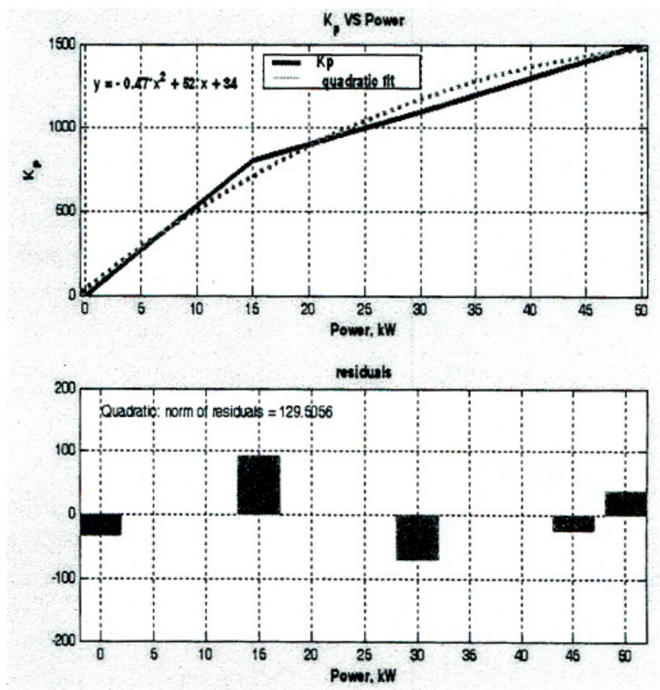

Figure 6: Second order fit

RESULTS

The relationship between the proportional gains and power was established with a second order polynomial.

The 200 kW generator DC voltage regulation was successfully tested at 12000 RPM with four load conditions from 0 to 5.1 kW. The proportional gains were automatically computed using the second order polynomial. Table 2 illustrates four load conditions from 0 to 5.1 kW and figure 7 shows the responses of the DC Current, DC Voltage.

POWER, kW	REG VOLTAGE, Volt DC	DC CURRENT
0	60	0
2.7	60	45
4.02	60	67
4.74	60	79
5.1	60	85

Table 2: K_p and K_i under different load conditions.

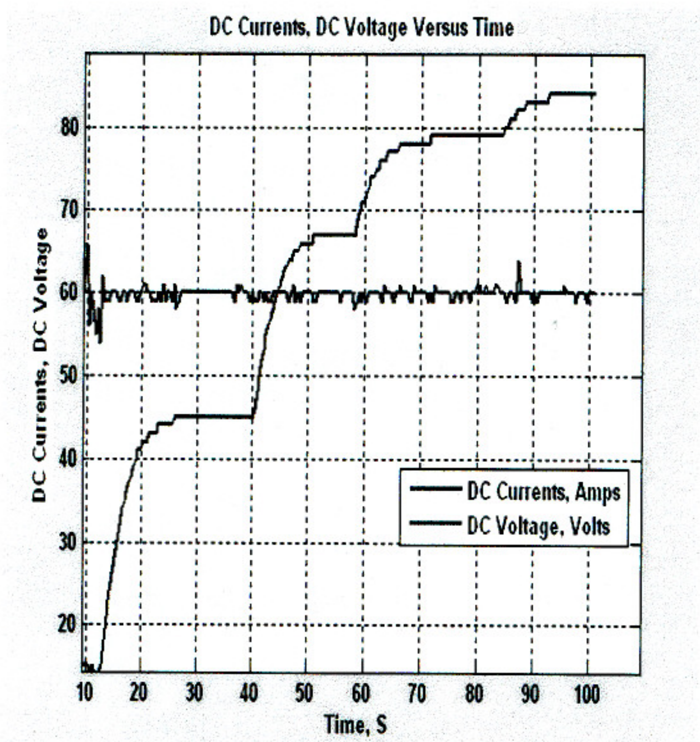

Figure 7: DC Current, DC Voltage Versus Time

CONCLUSION

The objective of this work was to develop closed control system to control the DC voltage output of the 200 kW induction generator using Field Oriented Control. Difficulties occurred in the beginning of the implementation using the classical proportional integrator controller. A gain scheduling control algorithm has been developed to solve this issue by selecting the appropriate controller gains with respect to the generator load. The gain scheduling control algorithm facilitates the understanding of the generator behavior which resulted in developing a better approach to control the DC voltage adaptively. Both methods were implemented successfully. However, the adaptive method is better approach because it can be tailored to work for high speed induction generators rated from 5 kW to 200 kW.

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REFERENCES

[1] Jay Vaidya, Earl Gregory, “High speed induction generator for application in aircraft power systems,” 2004 Power Systems Conference, Session: Advanced Power Systems Technologies I, Reno, NV, Nov. 2004.

[2] Karl J. Åström and Björn Wittenmark, Adaptive Control, Addison-Wesley, 1990.

[3] Ottman Elkhomri, “DSP implementation of DC Voltage Regulation using Adaptive Control for 200 kW 62000 rpm Induction Generator” Thesis for MSEE, University of Central Florida, 2006.

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